

ABSOLUTE MUSCLE FORCE IN THE ANKLE FLEXORS OF MAN

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All investigators since Weber [1846] are agreed that absolute muscle force should be regarded as tension per unit cross-section of the muscle because, as Weber indicated, the power of a muscle depends on its cross-section and not on its length. They are not agreed, however, on the exact definition of absolute muscle force. When the muscle is exerting its effort, should its fibres be at full stretch [Reys, 1915], half-way between full stretch and full shortening [Fick, 1910], or at 'the most favourable length' [Franke, 1920]? The results differ according to the criterion accepted. In many respects the methods previously used are unsound. The present study aims at establishing results on a more reliable basis.

The greatest resistance, against which plantar flexion of the ankle acts, can be determined and then translated into the maximum tension generated in the muscles producing the movement. Previous workers have increased the resistance by adding to the weight of the body [Weber, 1846; Reys, 1915] by applying a downward force to the lower end of the thigh [Hermann, 1898], or by an upward pressure on the ball of the foot [Reys, 1915]. Since the last appears to be the most precise method it was the one chosen for the present investigation.

METHODS

Maximum muscle force. The apparatus is shown in Fig. 1. The support behind the lumbar spine and pelvis was adjusted so that the knee could just be brought to the fully extended position. At this point the heel could be raised from the plank only by a maximum effort of ankle flexion. When the heel just cleared the plank an almost completely isometric contraction of the calf muscles was taking place in the position midway between full extension and full contraction. The leg and thigh were clear of the ground throughout the test. The distance of the head of the first metatarsal bone from the hinge was one-fifth of that between the hinge and the attachment of the spring

balance, so that the pressure on the ball of the foot was five times as great as the tension in the balance.

Rapid readings, made possible by use of a spring balance, are desirable in view of the quick onset of fatigue during strong muscle contractions. Reys [1915] used weights instead of a spring and he tested both legs together. His results for the pressure on the ball of the foot were only slightly higher than those of the present study, despite the fact that he was testing professional athletes.

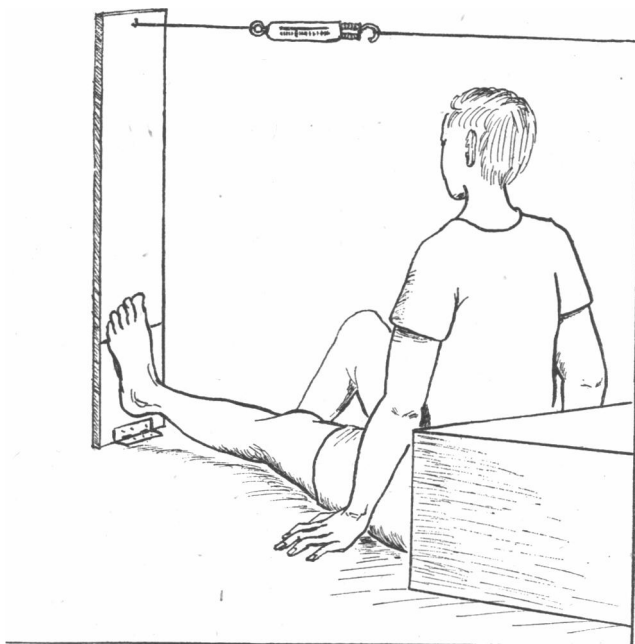


Fig. 1. Apparatus for measuring the maximum pressure on the ball of the foot against which ankle flexion can be exerted.

In order to obtain the actual tension in the calf muscles the foot must be studied as a lever. It matters not whether it is considered as a lever of the first class with the fulcrum at the ankle, as was done by the earlier workers, or as one of the second class with the fulcrum at the head of the first metatarsal [Reys, 1915; Martin, 1934], since, in equilibrium, the sum of the moments about any point is zero. The long controversy about the situation of the fulcrum does not, therefore, affect the calculation.

Five legs from anatomical subjects were cleared of all obstructing structures until free movement took place at the ankle joint with a minimum of friction. Each leg was held in clamps and spring balances were attached to the tendo calcaneus and to the foot at the level of the head of the first metatarsal bone

(Fig. 2). The readings on the two balances were taken when the foot had been pulled into slight plantar flexion by traction on the balance attached to the tendo calcaneus.

Cross-section of the ankle flexors in the cadaver. Weber [1846] estimated the area of cross-section of the calf muscles by dividing the volume by the length. It was realized by later workers that this gave only the mean anatomical cross-section, or area of section at right angles to the long axis of the muscles, and that what was required was the total physiological cross-section, or area of section of all the fibres at right angles to their long axes. The measurement of the latter, in muscles of complicated structure and with varying direction of fibre, is a difficult matter, and the methods used by Buchner [cited by Fick, 1910], Hermann [1898], Grohmann & Fick [see Fick, 1910], Reys [1915], and Franke [1920] must all be regarded as inaccurate.

The only way in which the physiological cross-section of a muscle can be found is to break up the muscle into bundles of parallel fibres and then to determine the total cross-section of these bundles. Examination of the gastrocnemius and soleus muscles revealed that they can be divided into a series of strips the component fibres of which are in a unipennate arrangement. In the case of the gastrocnemius two such strips, one for each head, were obtained, and in the soleus three. In each strip the proximal fibres were sectioned

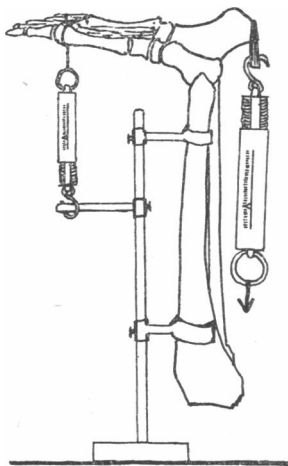


Fig. 2. Method of determining the ratio between the tension in the tendo calcaneus and the pressure on the ball of the foot.

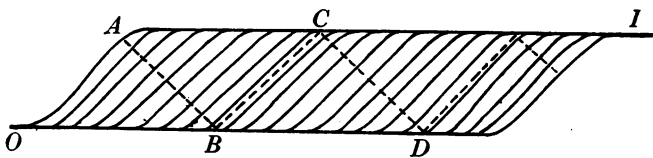


Fig. 3. Method of sectioning a unipennate muscle to obtain the physiological cross-section (see text). *OBD* is the tendon of origin and *ACI* the tendon of insertion of the muscle fibres.

at right angles to their length (*AB* in Fig. 3). At *B* a plane of cleavage *BC* was found between the last fibres cut and the first fibres still attached to the tendon of origin, and the portion *ABC* was detached. The remainder of the strip was sectioned and split alternately until all the fibres had been cut across. The total area of the cut surfaces *AB*, *CD*, etc., was determined by making outline tracings on celluloid of a uniform thickness, as recommended by Scammon & Scott [1927] and by Mainland [1929, 1933, 1934]. Six tracings

were made from each surface in order to reduce errors due to technique. Each tracing was cut out and weighed, and the area was calculated from the weight. These cadaver muscles were in the usual fully contracted position of complete plantar flexion, and allowance had to be made for this. Since human muscle fibres contract by 57% of their extended length [Haines, 1934], and since muscle volume remains constant [Glisson, 17th century], the physiological cross-section must diminish by 57% between full shortening and full extension, and at the half-way position it is 72% of the area at complete shortening. Furthermore, the muscle fibres are inclined at an angle to the tendon of insertion so that only a resolved component of the tension developed in the fibres acts in the line of the tendon. To allow for this, the physiological cross-section must be multiplied by the cosine of the angle between the fibres and the tendon. The result, called the 'reduced physiological cross-section', is used in subsequent calculations. In effect, this manoeuvre substitutes for the fibres acting at an angle to the tendon a bundle of smaller section acting in the line of the tendon.

Calculation of cross-section of the ankle flexors in life. Fick [1910], and others, applied the results obtained from cadaver muscles directly to the living, in the belief that formalin fixation produces no change in the dimensions of muscles. In the preserved legs used in the present work, however, the circumference in the region of the calf was much less than that in living subjects with a minimum of superficial fascia, so it was obvious that, in these specimens at least, the muscles were of smaller cross-section than those of the living subjects. To overcome this difficulty, the reduced physiological cross-section of the ankle flexors in the cadaver was divided by the anatomical cross-section of the cadaver leg in the region of the calf. The resulting figure was then multiplied by the anatomical cross-section of the living leg at the same level. The final figure represented the reduced physiological cross-section of the ankle flexors in the living subject. The anatomical cross-section of the leg both in cadaver and living subjects was determined by dividing the square of the circumference of the leg at the calf, measured with the ankle in full plantar flexion, by 4π . This is justifiable since the limb is almost circular at that level. Because the bones do not vary significantly in cross-section they were separated from the variable cross-section by subtraction of their sectional area.

RESULTS

The ratio of the tension in the tendo calcaneus to the resistance at the ball of the foot, determined from cadaver limbs, was 2.67 ± 0.038 (s.e. of mean of 5 observations) to 1. The constancy of this ratio allows of its application to living subjects in calculating the tension in the tendo calcaneus (Table 1).

The different cross-sections in the cadaver limbs are shown in Table 2. For the calculation of the reduced physiological cross-section the angle be-

TABLE 1. The maximum tension developed in the tendo calcaneus with the ankle half-way between full extension and flexion, obtained by multiplying the reading on the balance by 5×2.67

Subject	Reading		Maximum tension	
	Right leg kg.	Left leg kg.	Right leg kg.	Left leg kg.
R.G.	35	36	467.2	480.5
A.H.	37	35	493.8	467.2
M.H.	24	23	327.8	314.5
J.W.	30	30	400.5	400.5
D.K.	33	34	440.5	453.8
C.H.	37	39	493.8	520.5

TABLE 2. The relation of the reduced physiological cross-section of the ankle flexors to the anatomical cross-section of the leg in preserved limbs

Specimen	Physiol. C.S.	Red. phys. C.S.	Circum-	Anat. C.S.	A/B
	sq.cm.	'A' sq.cm.	ference cm.	'B' sq.cm.	
1	77.6	50.0	23.5	35.7	1.29
2	91.6	59.5	25.5	46.5	1.28
3	88.7	57.0	24.7	43.5	1.32
4	87.5	56.1	24.3	41.8	1.34

tween the muscle fibres and the tendon of insertion was found to be 10.5° for the gastrocnemius and 25° for the soleus, with the muscles in the mid-position. The ratio of the reduced physiological cross-section to the anatomical cross-section in the cadaver was a fairly constant one of 1.31 ± 0.024 (4) to 1. It seemed justifiable to assume that it holds for living subjects with a minimum of superficial fascia, and so it was used in calculating the reduced physiological cross-section in life from the anatomical cross-section (Table 3).

TABLE 3. The reduced physiological cross-section in living subjects, obtained by multiplying the anatomical cross-section by 1.31, and the absolute muscle force for the ankle flexors in the mid-position

Subject	Leg	Circum-	Anat. C.S.	Red. phys. C.S.	Absolute muscle force
		ference cm.			
R.G.	Right	35.9	97.3	127.5	3.66
	Left	35.6	95.6	125.2	3.83
A.H.	Right	35.5	95.0	124.5	3.97
	Left	35.5	95.0	124.5	3.75
M.H.	Right	30.0	66.4	87.0	3.86
	Left	30.0	66.4	87.0	3.62
J.W.	Right	32.2	77.3	101.3	3.95
	Left	32.2	77.3	101.3	3.95
D.K.	Right	34.0	86.8	113.7	3.88
	Left	34.0	86.8	113.7	3.99
C.H.	Right	35.5	95.0	124.5	3.97
	Left	35.5	95.0	124.5	4.18

Absolute muscle force. From the maximum muscle tension and the reduced physiological cross-section the absolute muscle force for the ankle flexors in the mid position was found to be 3.9 ± 0.15 (12) kg. per sq. cm. Previous

estimates of the absolute muscle force in these muscles were 0.836 kg. per sq. cm. [Weber, 1846], 5.9 kg. per sq. cm. [Knorz, cited by Franke, 1920], 6.24 kg. per sq. cm. [Hermann, 1898], 5.25 kg. per sq. cm. [Reys, 1915].

DISCUSSION

In combining data from living and preserved limbs certain assumptions must be made, for example, that the ratio of the physiological cross-section of the muscles to the anatomical cross-section of the limb is the same in living and preserved limbs. It is recognized, therefore, that the error in the results may be considerable. The method described here can, however, justifiably be claimed to give a more accurate estimate of the absolute muscle force than any previously used, because it considers the alteration in cross-section with stretching or shortening and the variations in size of the calf muscles in different individuals. In addition, previous workers have considered, from measurement of distances, that the tension in the tendo calcaneus is three times the resistance at the ball of the foot; the present method gives a more direct and more accurate result.

Only the muscles which act through the tendo calcaneus are considered to be effective in producing ankle flexion. The tendons of the other muscles on the posterior aspect of the leg pass so close to the axis of the ankle joint that they act on that joint at an overwhelming mechanical disadvantage. Such is also the opinion of Reys [1915].

Since the power of a muscle decreases as the muscle shortens (von Schwann's law) and at the same time the physiological cross-section increases, it is obvious that the force per unit cross-section must decrease with shortening. Absolute muscle force, therefore, varies with the different positions of a muscle and should be defined as the series of maximum tensions produced by voluntary contraction per unit of physiological cross-section in all positions between the maximum and minimum normal lengths of the muscle. The result has here been determined for one position of the calf muscles, since changes in the ankle joint angle are difficult to measure with accuracy.

SUMMARY

1. Data obtained from living and preserved legs were used to determine (a) the maximum muscle force, (b) the physiological cross-section, and (c) the absolute muscle force of the ankle flexors in man.

2. When the calf muscles were half-way between full extension and full contraction the maximum muscle force developed in the tendo calcaneus of six subjects was of the order of 438 kg. The physiological cross-section averaged 112.9 sq.cm., and the absolute muscle force was 3.9 kg. per sq.cm.

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